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Title: **METHOD AND APPARATUS FOR MONITORING FUEL CELL VOLTAGES**

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Field of the invention

[0001] The present invention relates to a voltage monitoring system and a method for measuring cell voltages. The invention has particular, but not exclusive, application to an electrochemical cell stack in which electrochemical cells are stacked in series.

Background of the invention

[0002] A fuel cell is an electrochemical device that produces an electromotive force by bringing the fuel (typically hydrogen) and an oxidant (typically air) into contact with two suitable electrodes and an electrolyte. A fuel, such as hydrogen gas, for example, is introduced at a first electrode where it reacts electrochemically in the presence of the electrolyte to produce electrons and cations in the first electrode. The electrons are circulated from the first electrode to a second electrode through an electrical circuit connected between the electrodes. Cations pass through the electrolyte to the second electrode. Simultaneously, an oxidant, such as oxygen or air is introduced to the second electrode where the oxidant reacts electrochemically in the presence of the electrolyte and a catalyst, producing anions and consuming the electrons circulated through the electrical circuit. The cations are consumed at the second electrode. The anions formed at the second electrode or cathode react with the cations to form a reaction product. The first electrode or anode may alternatively be referred to as a fuel or oxidizing electrode, and the second electrode may alternatively be referred to as an oxidant or reducing electrode. The half-cell reactions at the first and second electrodes respectively are:

$$H_2 \rightarrow 2H^+ + 2e^- \quad (1)$$

$$1/2O_2 + 2H^+ + 2e^- \rightarrow H_2O \quad (2)$$

[0003] An external electrical circuit withdraws electrical current and thus receives electrical power from the fuel cell. The overall fuel cell reaction produces electrical energy as shown by the sum of the separate half-cell

reactions shown in equations 1 and 2. Water and heat are typical by-products of the reaction.

[0004] In practice, fuel cells are not operated as single units. Rather, fuel cells are connected in series, either stacked one on top of the other or placed side by side. The series of fuel cells, referred to as a fuel cell stack, is normally enclosed in a housing. The fuel and oxidant are directed through manifolds in the housing to the electrodes. The fuel cell is cooled by either the reactants or a cooling medium. The fuel cell stack also comprises current collectors, cell-to-cell seals and insulation while the required piping and instrumentation are provided external to the fuel cell stack. The fuel cell stack, housing and associated hardware constitute a fuel cell module.

[0005] Various parameters have to be monitored to ensure proper fuel cell stack operation and to prevent damage of any of the fuel cells. One of these parameters is the voltage across each fuel cell in the fuel cell stack hereinafter referred to as cell voltage. Ideally, differential voltage measurement is done at the two terminals (i.e. anode and cathode) of each fuel cell in the fuel cell stack. However, since fuel cells are connected in series, and typically in large number, measuring cell voltage for each cell is often prohibitively expensive and troublesome. A common compromise that is made in the art is measuring voltages across groups of cells within a fuel cell stack.

[0006] An example of this type of fuel cell voltage monitoring system is disclosed by Blair et al. in US Patent No. 5,170,124. In this patent, fuel cells within a fuel cell stack are divided into a plurality of groups and the voltage across each fuel cell group is measured. Then the measured voltage of each fuel cell group is normalized, i.e. averaged according to the number of fuel cells in the group. The normalized voltage of each fuel cell group is then compared with a reference voltage equal to a predetermined minimum voltage. If the normalized measured voltage is less than the reference voltage, an alarm can be activated. Another example of a fuel cell voltage

monitoring system that utilizes averaged cell voltages is disclosed by Zeilinger et al in US Patent No. 6,432,569.

[0007] Although such fuel cell voltage monitoring systems alleviate the problems of measuring every cell voltage while meeting the requirement of monitoring cell performance, only average cell voltages are obtainable from these systems. In reality, it is more than likely that one or more cells in a fuel cell group has a voltage considerably lower than those of the others while the average cell voltage of that fuel cell group is still well above the predetermined minimum cell voltage. In this case, the fuel cell voltage monitoring system will not be able to detect the poor performance of the "bad cell" and activate an alarm and hence a corresponding recovery operation cannot be initiated in a timely manner. This will eventually lead to damage of the fuel cell stack and power shutdown.

Summary of the invention

[0008] In order to overcome the problems associated with current methods of measuring cell voltage, the present invention provides a cell voltage monitoring system and method that can estimate the minimum cell voltage within a cell stack. The estimated minimum cell voltage is used as an indication of cell performance rather than relying on measuring average cell voltage. The inventors have found that this measurement scheme provides a more accurate indication of cell performance with the added benefit of not having to measure each cell voltage in the cell stack. When the estimated minimum cell voltage drops below a certain value, a correction operation or shutdown can be performed for the cell stack.

[0009] In accordance with a first aspect, the present invention provides a method for monitoring cell voltages for a plurality of electrochemical cells connected in series forming a cell stack. The method comprises:

a) dividing the plurality of electrochemical cells into at least two cell groups;

b) determining an average cell stack voltage V_{sa};

c) measuring a cell group voltage V_g for each cell group;

d) estimating a minimum cell voltage V_{mi} for each cell group to obtain a set of minimum cell voltages; and,

e) determining a minimum cell voltage V_{min} for the cell stack by finding the minimum value in the set of minimum cell voltages.

[0010] The minimum cell voltage for one of the cell groups is estimated according to $V_{mi} = \frac{V_g}{M} - \frac{(N-M)*V_{ss}}{M}$ where N is a number of cells in the cell group, and M is an estimated number of cells operating below the average cell stack voltage.

[0011] In accordance with a second aspect, the present invention provides a voltage monitoring system for monitoring cell voltages for a plurality of electrochemical cells connected in series forming a cell stack. The plurality of cells are divided into at least two cell groups. The voltage monitoring system comprises a voltage measuring unit for measuring cell group voltage V_g for each cell group, and cell stack voltage V_s for the cell stack. The voltage monitoring system also comprises a processing means connected to the voltage measuring unit for calculating an average cell stack voltage V_{sa}, estimating a cell group minimum cell voltage V_{mi} for each cell group to obtain a set of minimum cell voltages, and determining a minimum cell voltage V_{min} for the cell stack by finding the minimum value in the set of minimum cell voltages.

[0012] The processing means estimates the minimum cell voltage for one of the cell groups according to $V_{mi} = \frac{V_g}{M} - \frac{(N-M)*V_{ss}}{M}$ where N is a number of cells in the cell group, and M is an estimated number of cells operating below the average cell stack voltage.

[0013] In accordance with another aspect, the present invention provides a method for monitoring cell voltages for a plurality of

electrochemical cells connected in series forming a cell stack. The method comprises:

a) dividing the plurality of electrochemical cells into at least two cell groups;

b) determining an average cell stack voltage V_{sa};

c) measuring a cell group voltage V_g for one of the cell groups;

d) estimating a minimum cell voltage V_{mi} for the one of the cell groups;

e) comparing the minimum cell voltage V_{mi} to a threshold value; and,

f) repeating steps c, d and e until one of the minimum cell voltages V_{mi} is less than or equal to the threshold value or the minimum cell voltage for each of the cell groups has been estimated.

[0014] In accordance with another aspect, the present invention provides a voltage monitoring system for monitoring cell voltages for a plurality of electrochemical cells connected in series forming a cell stack, the plurality of cell groups being divided into at least two cell groups. The voltage monitoring system comprises a voltage measuring unit for measuring a cell group voltage V_g for each cell group, and cell a stack voltage V_s for the cell stack. The voltage monitoring system further comprises a processing means connected to the voltage measuring unit for calculating an average cell stack voltage V_{sa}, repeatedly estimating a cell group minimum cell voltage V_{mi} for one of the cell groups and comparing the minimum cell voltage V_{mi} to a threshold value until one of the minimum cell voltages V_{mi} is less than or equal to the threshold value or the minimum cell voltage V_{mi} for each of the cell groups has been estimated.

Brief description of the drawings

[0015] For a better understanding of the present invention and to show more clearly how it may be carried into effect, reference will now be made, by

way of example, to the accompanying drawings which show a preferred embodiment of the present invention and in which:

[0016] Figure 1 is a block diagram of an electrochemical cell stack divided into a plurality of cell groups;

[0017] Figure 2 is a block diagram illustrating the cell voltages in one of the cell groups of Figure 1; and,

[0018] Figure 3 is a block diagram of a fuel cell voltage monitoring system that estimates minimum cell voltage in accordance with the present invention.

Detailed description of the invention

[0019] Referring first to Figure 1, shown therein is an electrochemical cell stack **10**, which may be a battery or a fuel cell stack, comprising a plurality of cells **12** stacked in series (only one of the cells is labeled for simplicity). Each cell **12** typically generates a voltage of about 0.6 to 1.0 volts. The plurality of cells **12** is divided into a plurality of cell groups. Each cell group can have the same number of cells. Alternatively, at least one of the cell groups does not have to have the same number of cells as the other cell groups. For example, as shown in Figure 1, the electrochemical cell stack **10** comprises 20 cells divided into 4 cell groups in which cell group 1 consists of 5 cells, cell group 2 consists of 4 cells, cell group 3 consists of 6 cells and group cell 4 consists of 5 cells. In practice, the number of cell groups within the electrochemical cell stack **10** and the number of cells within each cell group can be selected according to actual system requirements.

[0020] Group cell voltages $\mathbf{V_{gi}}$ are measured across the two ends of each cell group. A stack voltage $\mathbf{V_s}$ is also measured across the whole electrochemical cell stack **10**. The overall stack voltage $\mathbf{V_s}$ is then divided by the total number of cells in the electrochemical cell stack **10** to obtain an average cell stack voltage $\mathbf{V_{sa}}$

[0021] Referring now to Figure 2, shown therein is a block diagram illustrating exemplary cell voltages for cell group 2 of Figure 1. It is estimated

that within cell group 2, three of the cells, namely cells **14**, **16** and **18** are operating at the average cell stack voltage V_{as} and one cell, namely cell **20** is operating below the average cell stack voltage V_{as}, thereby decreasing the cell group voltage V_{g2}. In this case, the following equation can be can be used to obtain the cell group V_{g2}:

$$V_{g2} = V_{m2} + 3V_{sa} \tag{1}$$

where V_{m2} is the minimum cell voltage in the fuel cell group. Accordingly, the minimum cell voltage V_{m2} can be obtained from the following equation:

$$V_{m2} = V_{g2} - 3V_{sa} \tag{2}$$

[0022] In reality, there may be any number of cells operating below the average cell stack voltage V_{sa} within a specific fuel cell group. In the present invention, it is assumed each cell operating below the average cell stack voltage operates at the same cell voltage V_{mi}. Therefore, in general , the cell voltage V_{gi} for a cell group i can be obtained from the following equation:

$$V_{gi} = M^*V_{min} + (N-M)^*V_{sa} \tag{3}$$

where N is the number of cells within the cell group **i** and M is the estimated number of cells operating below the average cell stack voltage V_{sa}. Accordingly, M has a value that is less than or equal to N. Therefore, in general, the minimum cell voltage for the cell group i can be estimated as follows:

$$V_{mi} = \frac{V_{gi}}{M} - \frac{(N-M)*V_{sa}}{M} \tag{4}$$

[0023] Equation **4** is used to estimate the minimum cell voltage V_{mi} for a cell group i for any number of cells operating below the average cell stack voltage V_{sa} in the cell group i by setting the parameter M equal to the estimated number of cells that are operating under the average cell stack voltage V_{sa}. This estimation is done for each and every cell group within the electrochemical cell stack to obtain a set of minimum cell voltages V_{mi} from which the minimum cell voltage $V_{m\,i}$ can be found for the entire electrochemical cell stack **10**. In practice, voltage measurement for each cell group and the entire electrochemical cell stack **10** is performed at a certain

interval, for example every 10 ms. The minimum cell voltage $\mathbf{V_{mi}}$ is then estimated and used to determine whether or not the cells are operating at an acceptable condition. In general, the parameter M is a low value such as 1 whereas the number of cells N in a particular cell group is on the order of 4 to 6. However, as the number of cells N in the electrochemical cell stack **10** increases, the parameter M may be also be increased.

[0024] Referring now to Figure 3, shown therein is an exemplary embodiment of a fuel cell system **100** that incorporates a fuel cell voltage monitoring system **102** in accordance with the present invention. The fuel cell system **100** comprises a fuel cell stack **104**, a fuel storage vessel **106** and a compressor (or blower) **108**. The fuel storage vessel **106** contains fuel that is supplied to the fuel cell stack **104** via a fuel supply line **110**. The fuel supply line **110** includes a flow control valve **112** to regulate the amount of fuel that is supplied to the fuel cell stack **104**. The fuel cell stack **104** is also connected to a fuel discharge line **114** to discharge fuel from the fuel cell stack **104**. The compressor **108** supplies an oxidant, such as air, to the fuel cell stack **104** via an oxidant supply line **116**. The fuel cell stack **104** is also connected to an oxidant discharge line **118** for discharging oxidant exhaust.

[0025] The fuel cell voltage monitoring system **102** comprises a voltage measuring unit **120** and a processing unit **122**. The voltage measuring unit **120** is connected to the fuel cell stack **104** via a plurality of electrical lines or contacts **124** to measure the voltages across a plurality of cell groups within the fuel cell stack **104**. The voltage measuring unit **120** provides the measured cell group voltages $\mathbf{V_{gi}}$ as well as the stack voltage $\mathbf{V_s}$ to the processing unit **122**. The processing unit **120** then calculates the average cell stack voltage $\mathbf{V_{sa}}$ and estimates the minimum cell voltage $\mathbf{V_{mi}}$ for each cell group and the overall minimum cell voltage $\mathbf{V_{min}}$ for the entire fuel cell stack **104** in accordance with the present invention. The voltage measuring unit **120** may comprise a bank of differential amplifiers, or the like, with appropriate pre-processing circuitry for effecting the voltage measurements, as is commonly known to those skilled in the art. The processing unit **210** may be a

controller, or a microprocessor. There may be additional hardware components connected between the voltage measuring unit **120** and the processing unit **122** such as an analog-to-digital converter and a digital-to-analog converter.

[0026] The processing unit **122** uses the minimum cell voltage $\mathbf{V_{min}}$ to control the operation of the fuel cell system **100**. Once the processing unit **122** estimates the minimum cell voltage $\mathbf{V_{min}}$ of the entire fuel cell stack **104**, the processing unit **122** compares the minimum cell voltage $\mathbf{V_{min}}$ to a first threshold value, such as 0.5 V for example. When the minimum cell voltage $\mathbf{V_{min}}$ for the entire fuel cell stack **104** is equal to or less than the first threshold value, an alarm signal is activated. Preferably, the processing unit **122** controls components in the fuel cell system **100** to change the operating conditions in the fuel cell system **100** so that the cells that have a below average cell voltage can recover their cell voltages. For instance, in many cases, cell voltage drops because the cell is flooded with fuel. Accordingly, in this situation, the processing unit **122** controls the compressor **108** via a control line **126** to increase the speed of the compressor **108** to supply more oxidant to the fuel cell stack **104** and expel the accumulated water out of the flooded cell, thereby recovering cell voltage.

[0027] The processing unit **122** also compares the minimum cell voltage $\mathbf{V_{min}}$ for the entire fuel cell stack **104** to a second threshold value such as 0.3 V. When the minimum cell voltage $\mathbf{V_{min}}$ is equal to or less than the second threshold value, a shutdown signal is activated. The fuel cell system **100** can be shut down manually. However, and more preferably, the processing unit **122** can immediately shut down the fuel cell system **100** by shutting down the compressor **108** to stop the flow of oxidant and by closing the flow control valve **112**, by sending a control signal via control line **128**, to stop the supply of fuel.

[0028] It should be understood that Figure 3 shows an exemplary embodiment of a fuel cell system and that an actual fuel cell system may have different or additional components. Furthermore, it should be understood that

the voltage measuring unit **120** and the processing unit **122** repeatedly perform the voltage monitoring method of the present invention, and the comparisons with the threshold levels, during the operation of the fuel cell system **100**.

[0029] In an alternative, the minimum cell voltage V_{mi} for each cell group does not need to be estimated for each cell group if any of the estimated minimum cell voltages V_{mi} that are thus far estimated are smaller than the first or second thresholds. For instance, if there are 5 cell groups, and if after estimating the minimum cell voltages for the first two cell groups it is determined that one of the minimum cell voltages V_{mi} is smaller than the first or second threshold, then there is no need to estimate the remaining minimum cell voltages. A suitable action can be done based on this result. In the example of Figure 3, the processing unit **122** can perform the suitable action of shutting down the fuel cell system **100** or increasing the setting on the compressor **102** to provide more oxidant, as the particular situation dictates.

[0030] The present invention allows for adequate estimation of the minimum cell voltage within an electrochemical cell stack while avoiding the need to measure the voltage of every cell. It should be understood that the present invention is intended not only for monitoring the voltages of fuel cell stacks, but also for monitoring the voltages in any kind of multi-cell battery formed by connecting individual cells in series such as a battery bank or an electrolyser.

[0031] It should be further understood that various modifications can be made, by those skilled in the art, to the preferred embodiments described and illustrated herein, without departing from the present invention, the scope of which is defined in the appended claims.